

# Quantifying the information content of global imaging spectroscopy

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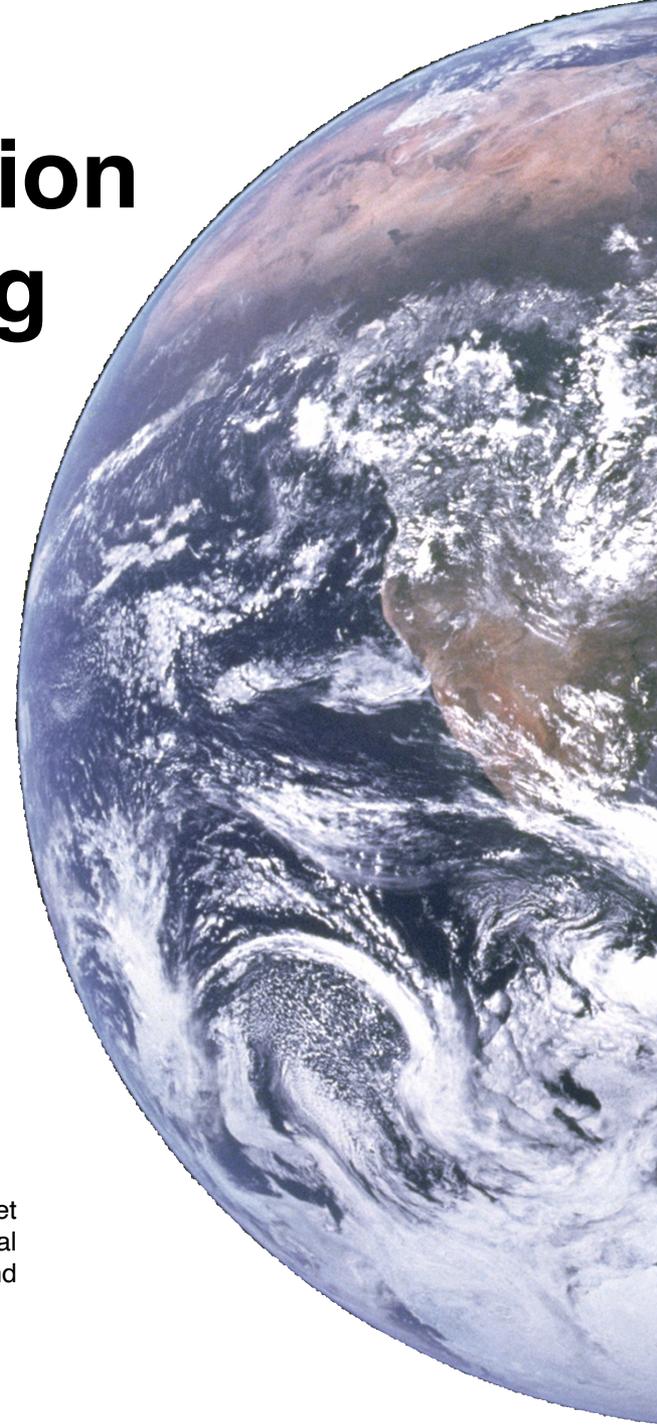
<sup>2</sup> Boston University

<sup>3</sup> Naval Research Laboratory

<sup>4</sup> University of Massachusetts

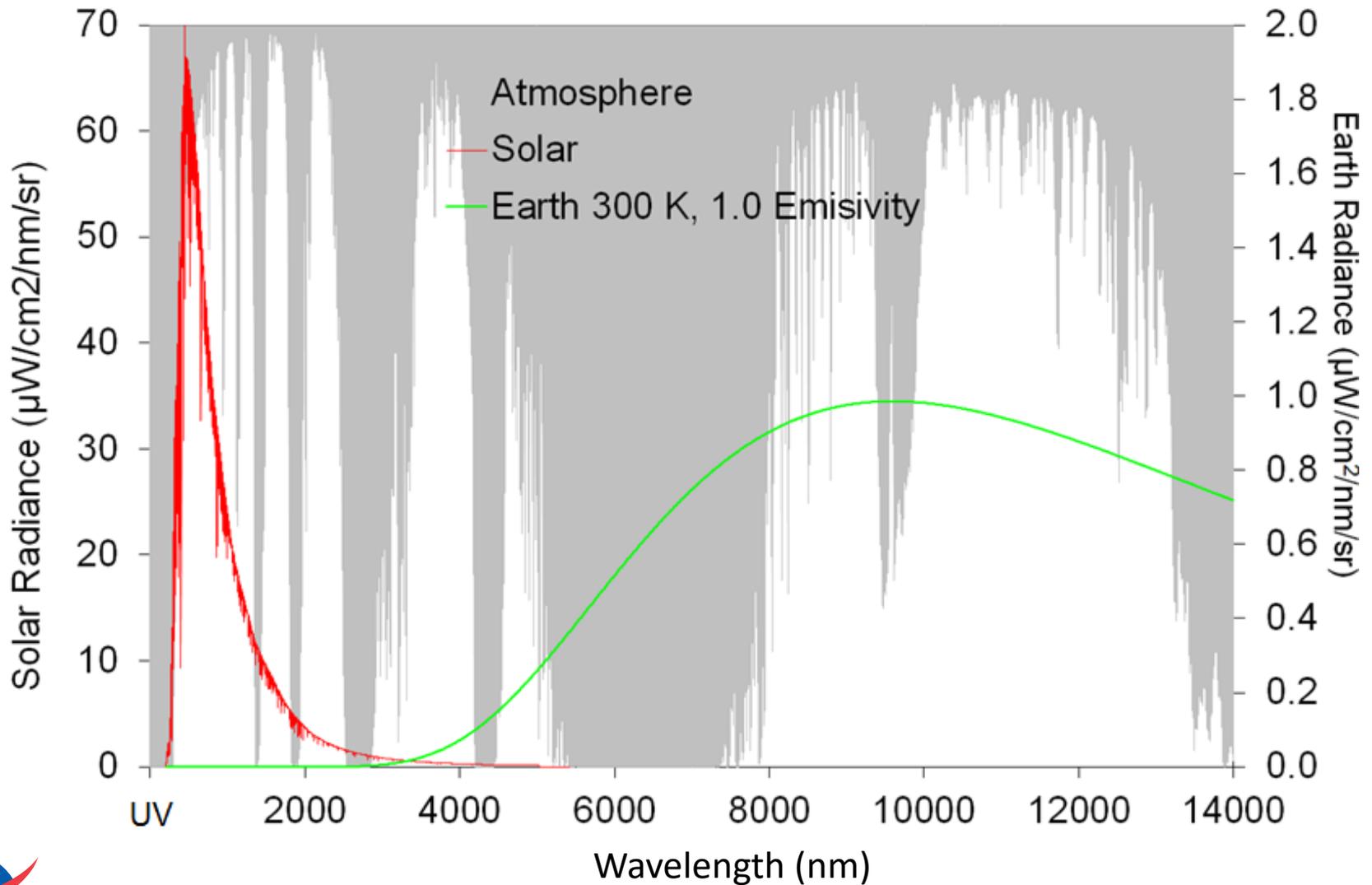


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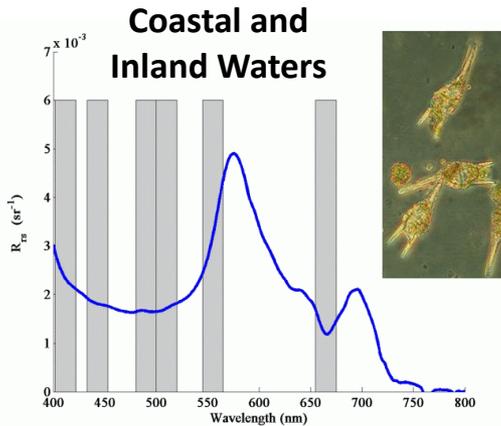
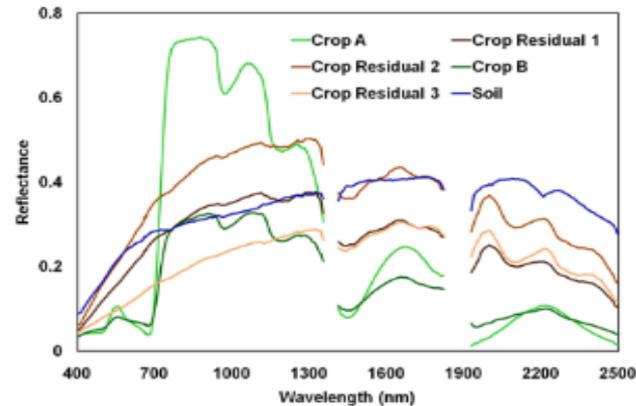
# Dramatis Personae



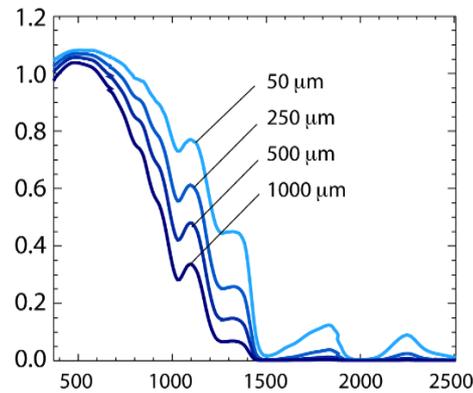
# VSWIR Spectroscopy Designated by the 2017 Decadal Survey

- 380 to 2500 nm @10 nm
- Approx. 30 m sampling of land and coastline
- Approx. biweekly coverage
- High SNR

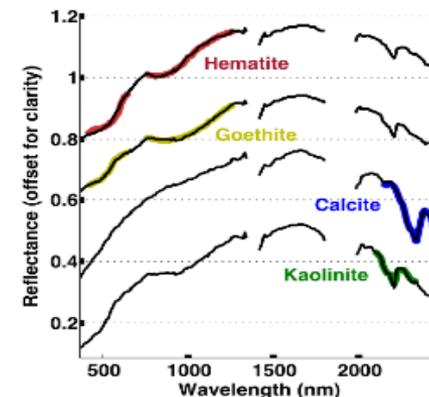
## Agriculture and Ecosystems



## Snow and Ice

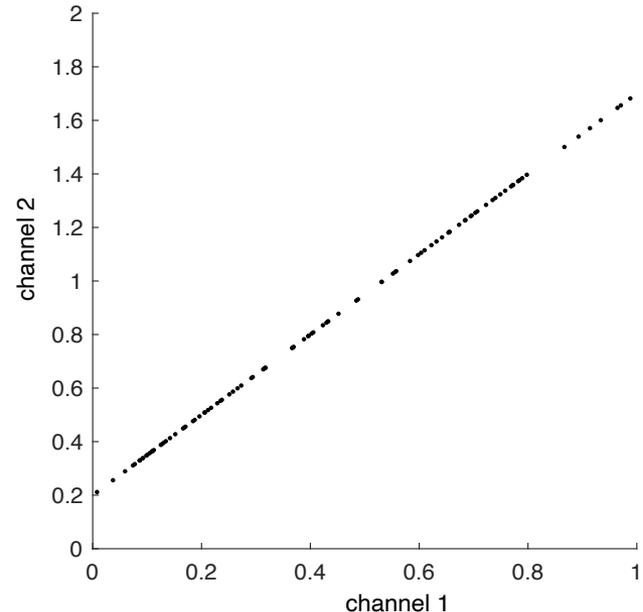
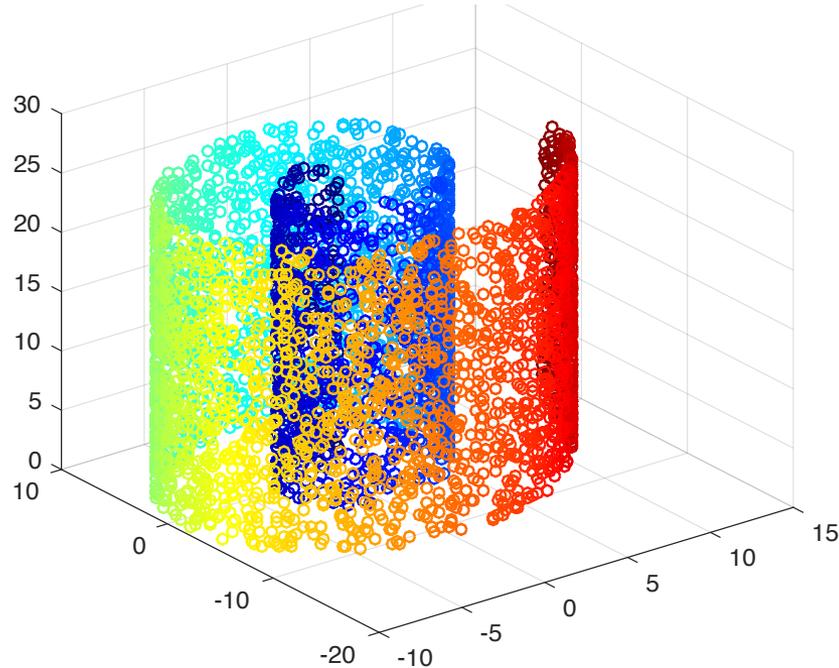


## Geology and Soils



# Intrinsic dimensionality

- The degrees of freedom in a process under study
- Characterize by analyzing the *Covariance Matrix* (linear case)

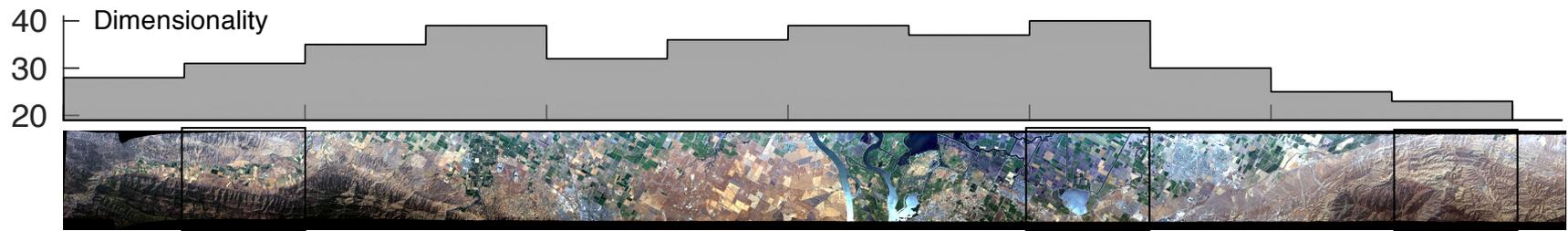


Laplacian Eigenmap code via Kye Taylor, Mathworks file exchange



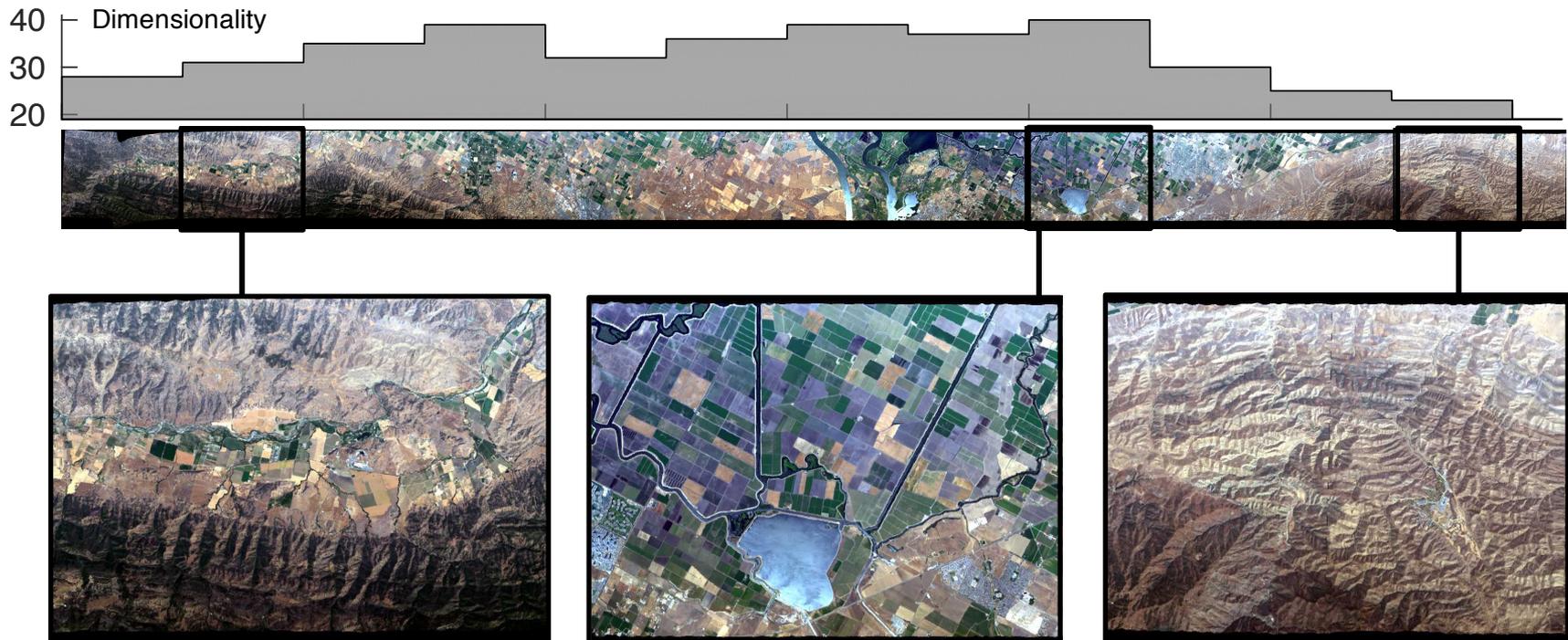
# Example: Dimensionality of AVIRIS-C Flightline Segments

[Thompson et al., *Optics Express* 2017]



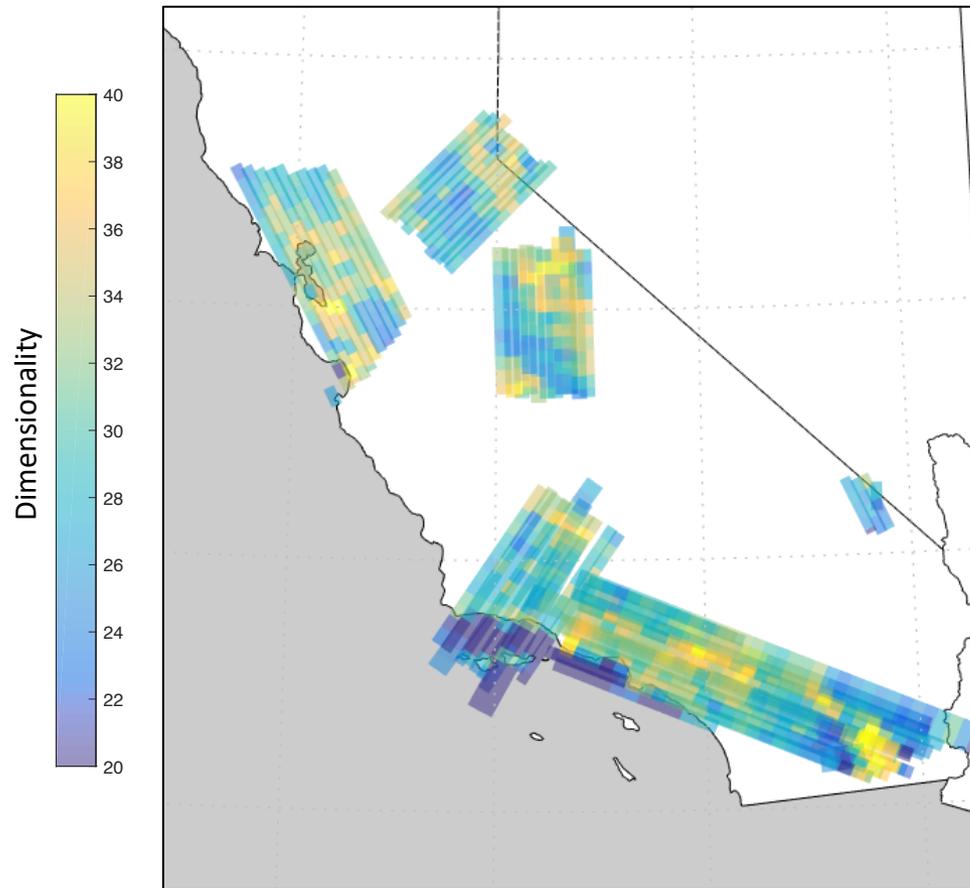
# Example: Dimensionality of AVIRIS-C Flightline Segments

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# Hot spots of spectral diversity

[Thompson et al., *Optics Express* 2017]



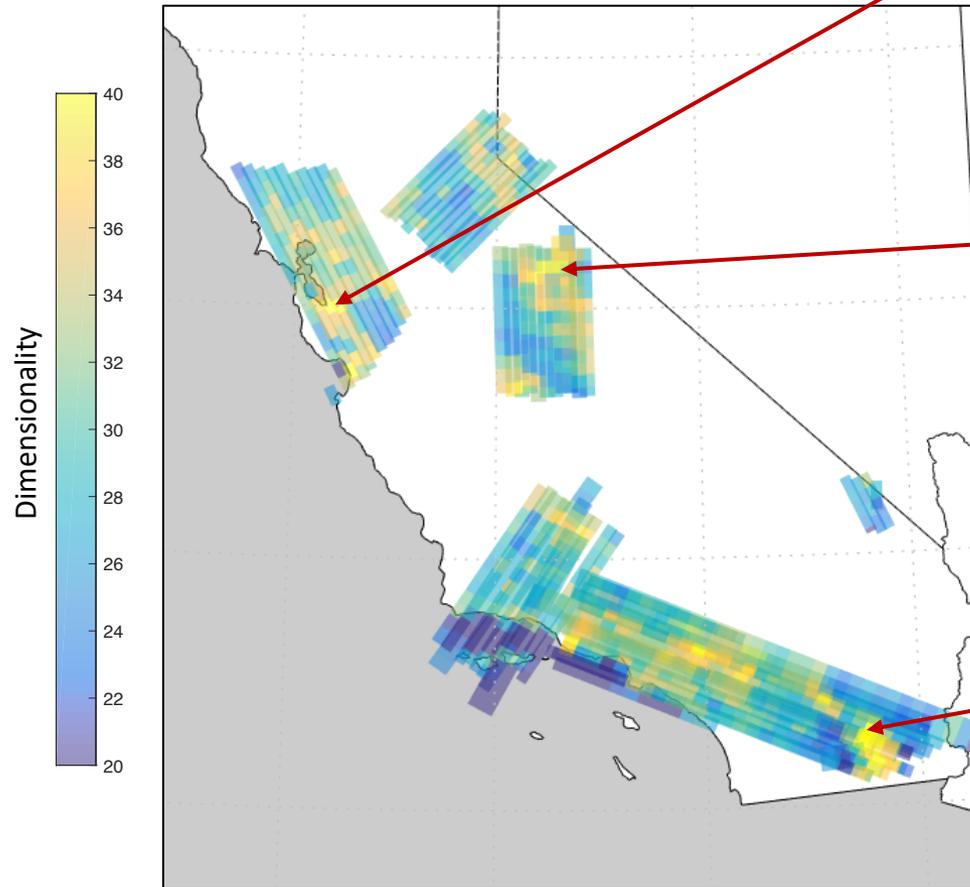
Images: Wikimedia/ Google / NASA / Sierra Nevada Photo by DAVID ILIFF. License: CC-BY-SA 3.0

5 March 2018

david.r.thompson@jpl.nasa.gov

# Hot spots of spectral diversity

[Thompson et al., *Optics Express* 2017]



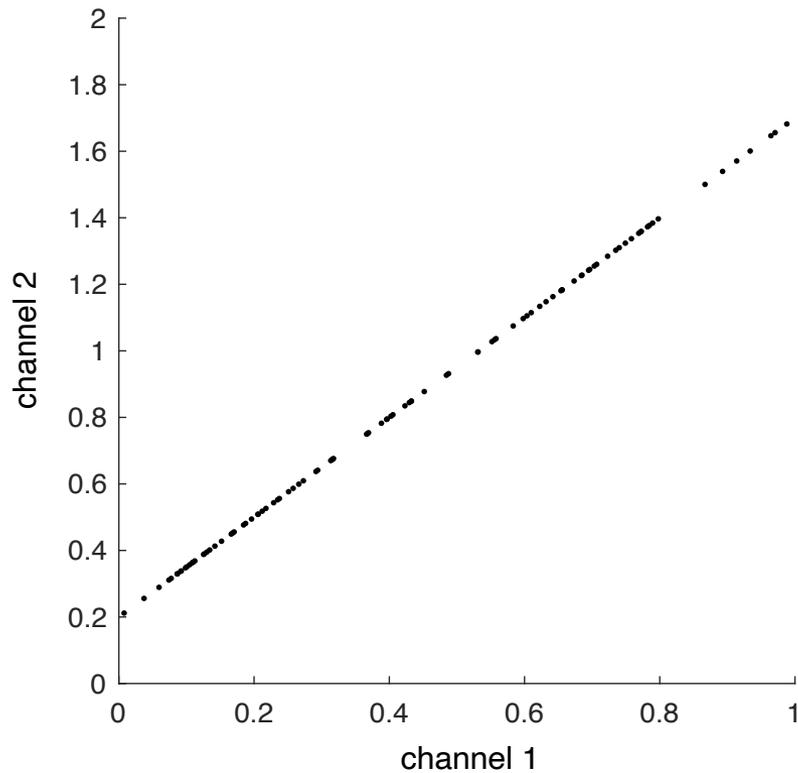
Images: Wikimedia/ Google / NASA / Sierra Nevada Photo by DAVID ILIFF. License: CC-BY-SA 3.0

5 March 2018

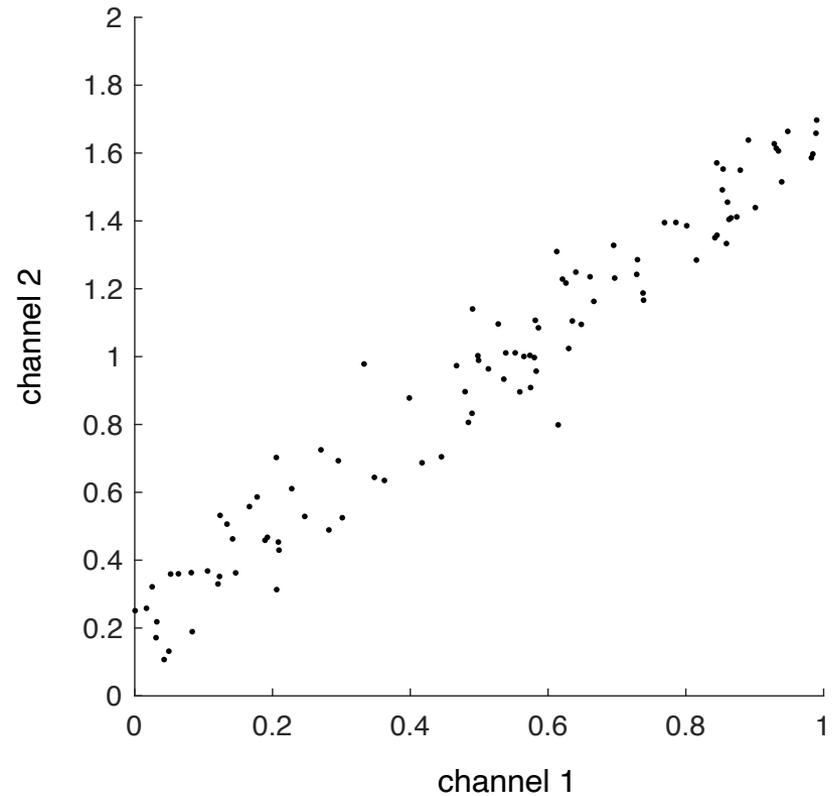
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# The challenge of irrelevant variance

Underlying process of interest



With measurement noise

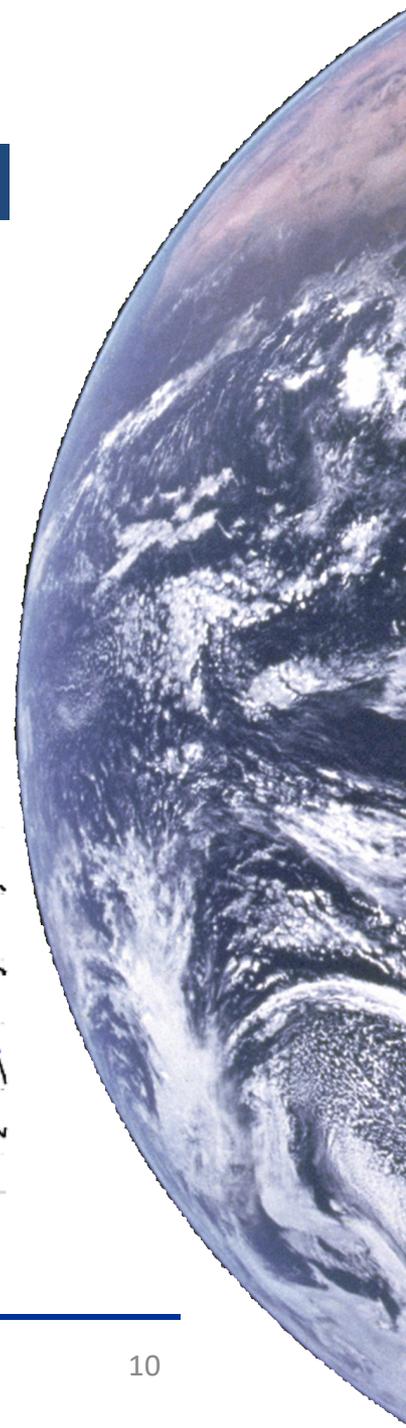
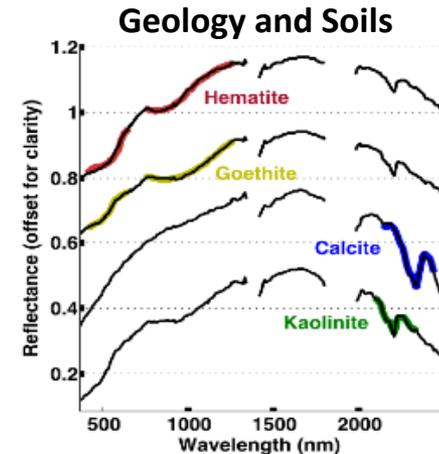
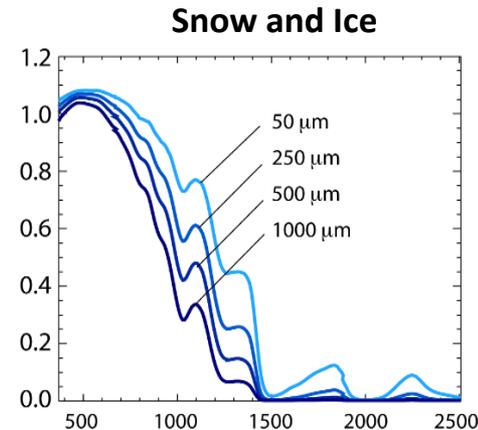
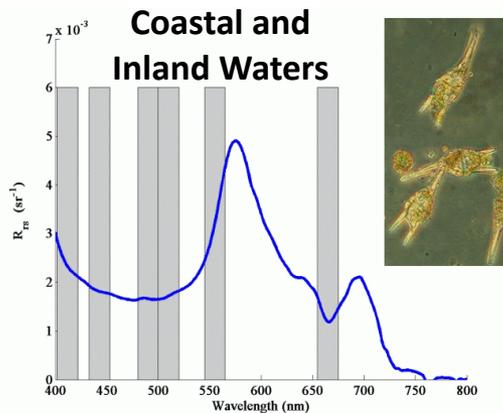
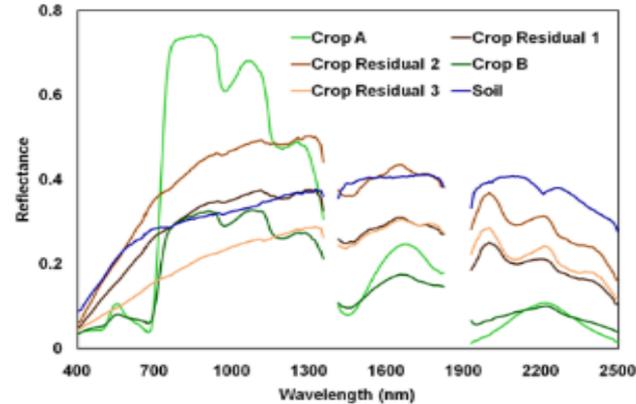


# Dimensionality of a retrieval

How does the dimensionality of a **specific population of reflectance spectra** survive remote observation?

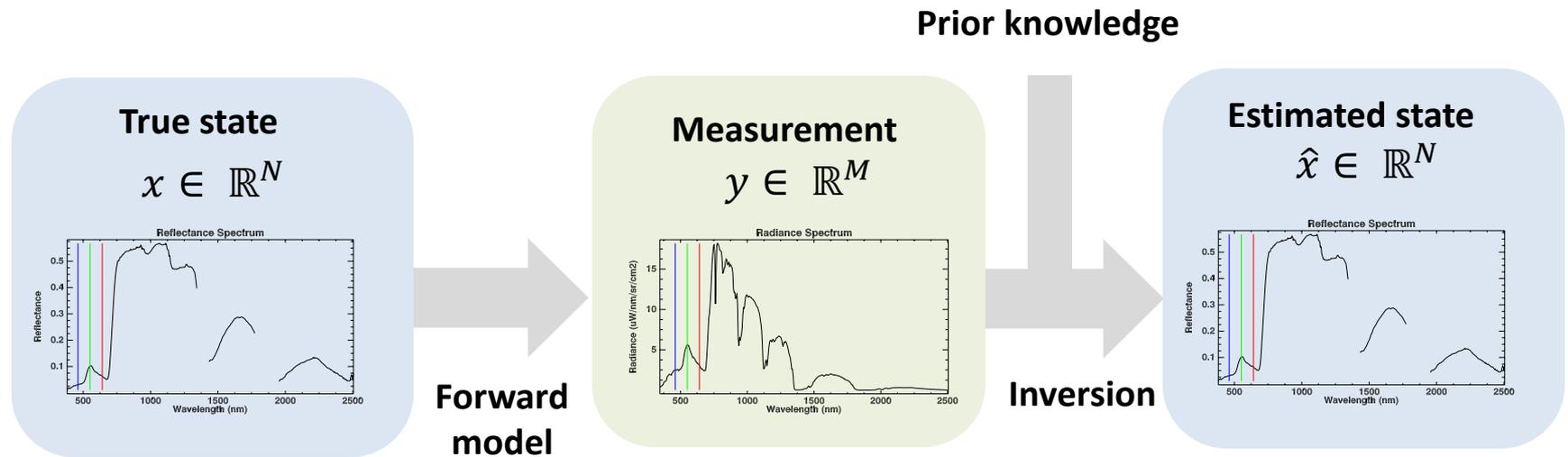
Can we design instruments and retrieval algorithms to conserve this information?

### Agriculture and Ecosystems



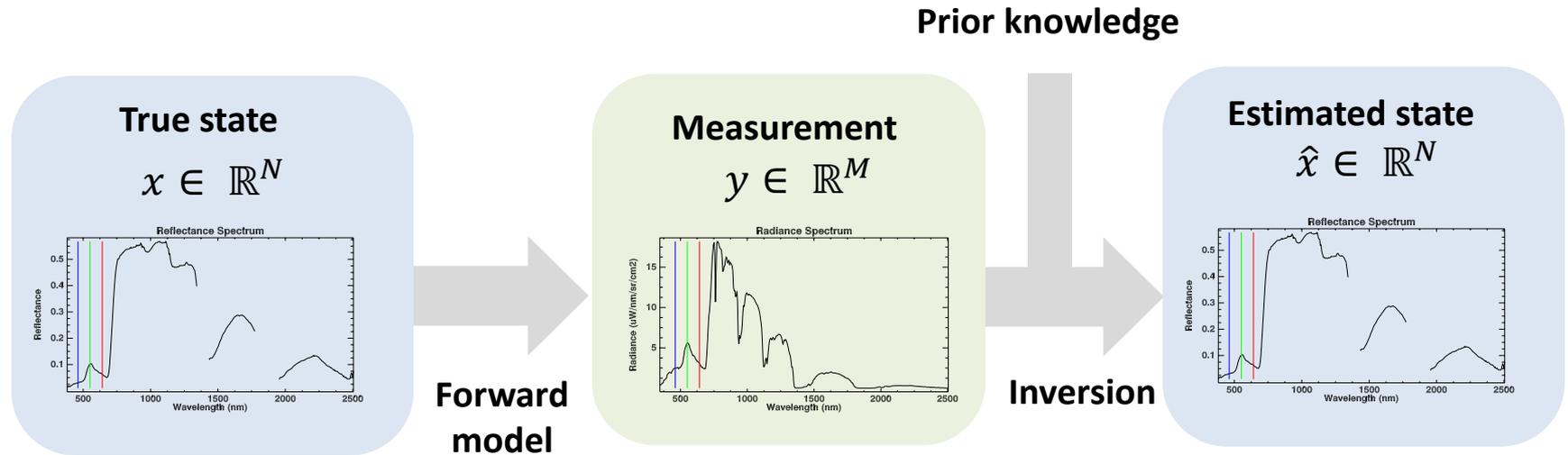
# Information flow in remote observing systems

[Rodgers 2000, Thompson et al., Remote Sens. Environ. 2018]



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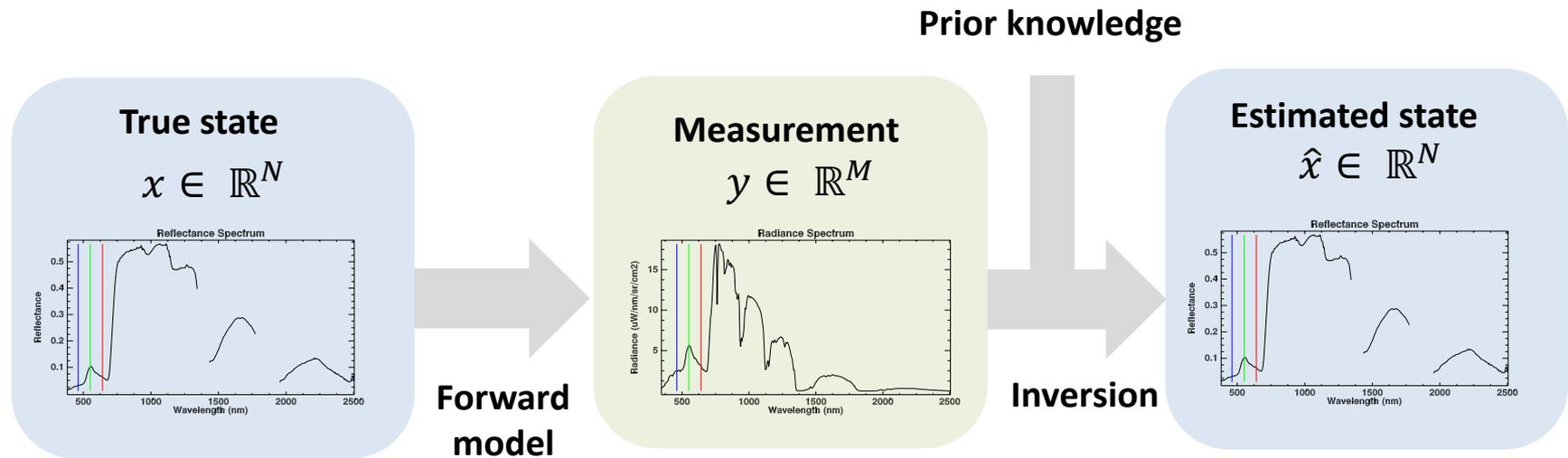
The averaging kernel matrix  $A$ :  
The change in the estimate due  
to the change in the true state  
(evaluated at the solution).

$$A = \frac{\partial \hat{x}}{\partial x}$$



# Information flow in remote observing systems

[Rodgers 2000, Thompson et al., Remote Sens. Environ. 2018]



The averaging kernel matrix  $A$ :  
The change in the estimate due  
to the change in the true state  
(evaluated at the solution).

$$A = \frac{\partial \hat{x}}{\partial x} = GK$$

Gain Matrix: sensitivity of  
inversion to a change in the  
observation

Jacobian: sensitivity of the  
observation to a change in  
the true state



# Inversion by Optimal Estimation

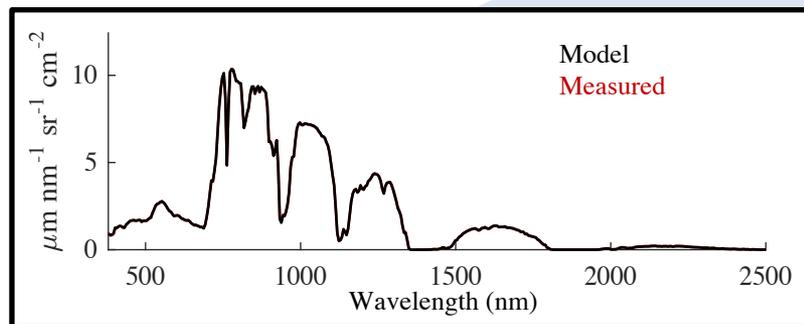
[Thompson et al., Remote Sensing of Environment 2018]

Bayesian *Maximum a Posteriori* estimate

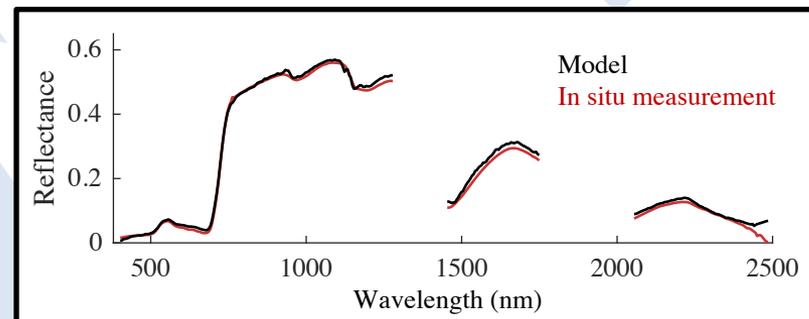
Comprehensive model of surface, atmosphere, instrument with uncertainties

Exploits information across the full spectrum for accurate atmospheric correction

<https://github.com/isofit/isofit>



Iterative optimization



# Inversion by Optimal Estimation

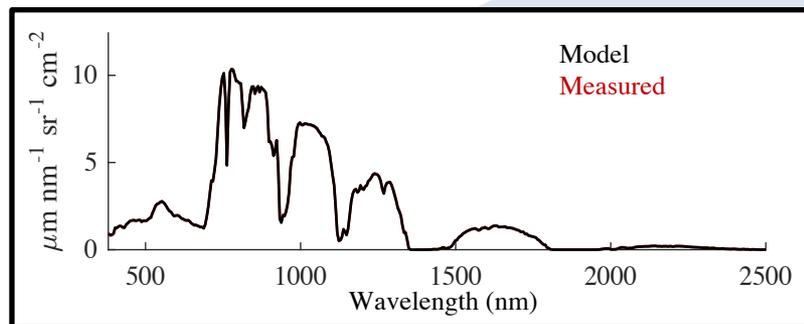
[Thompson et al., Remote Sensing of Environment 2018]

Bayesian *Maximum a Posteriori* estimate

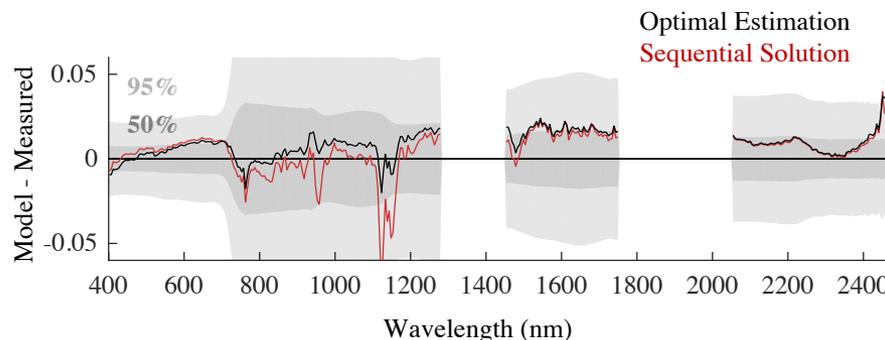
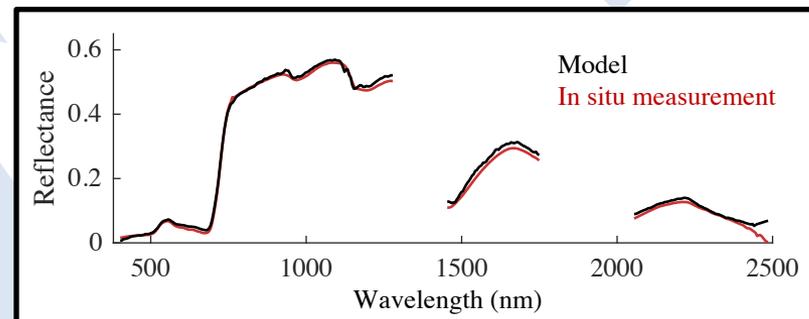
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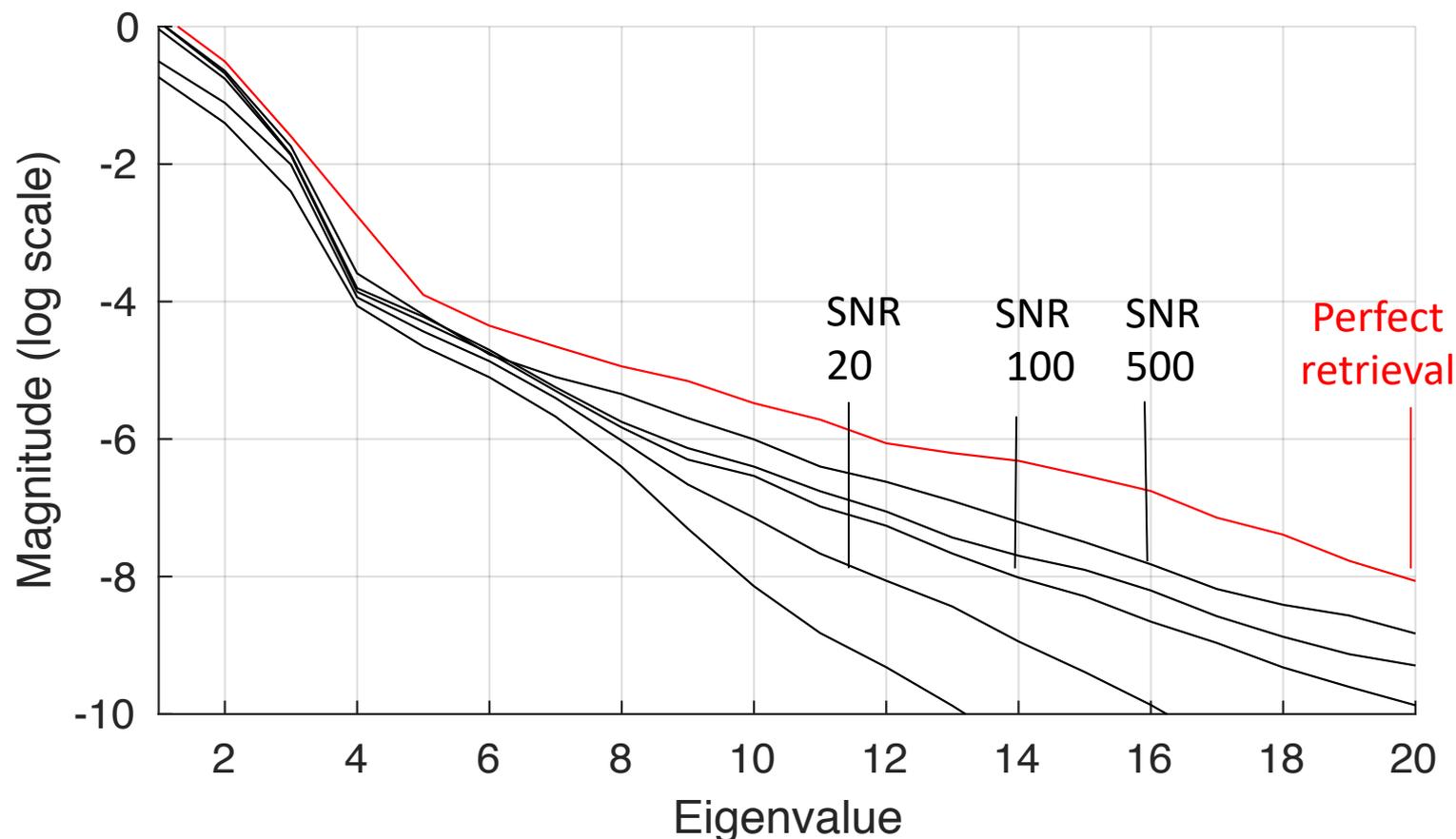
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Iterative optimization

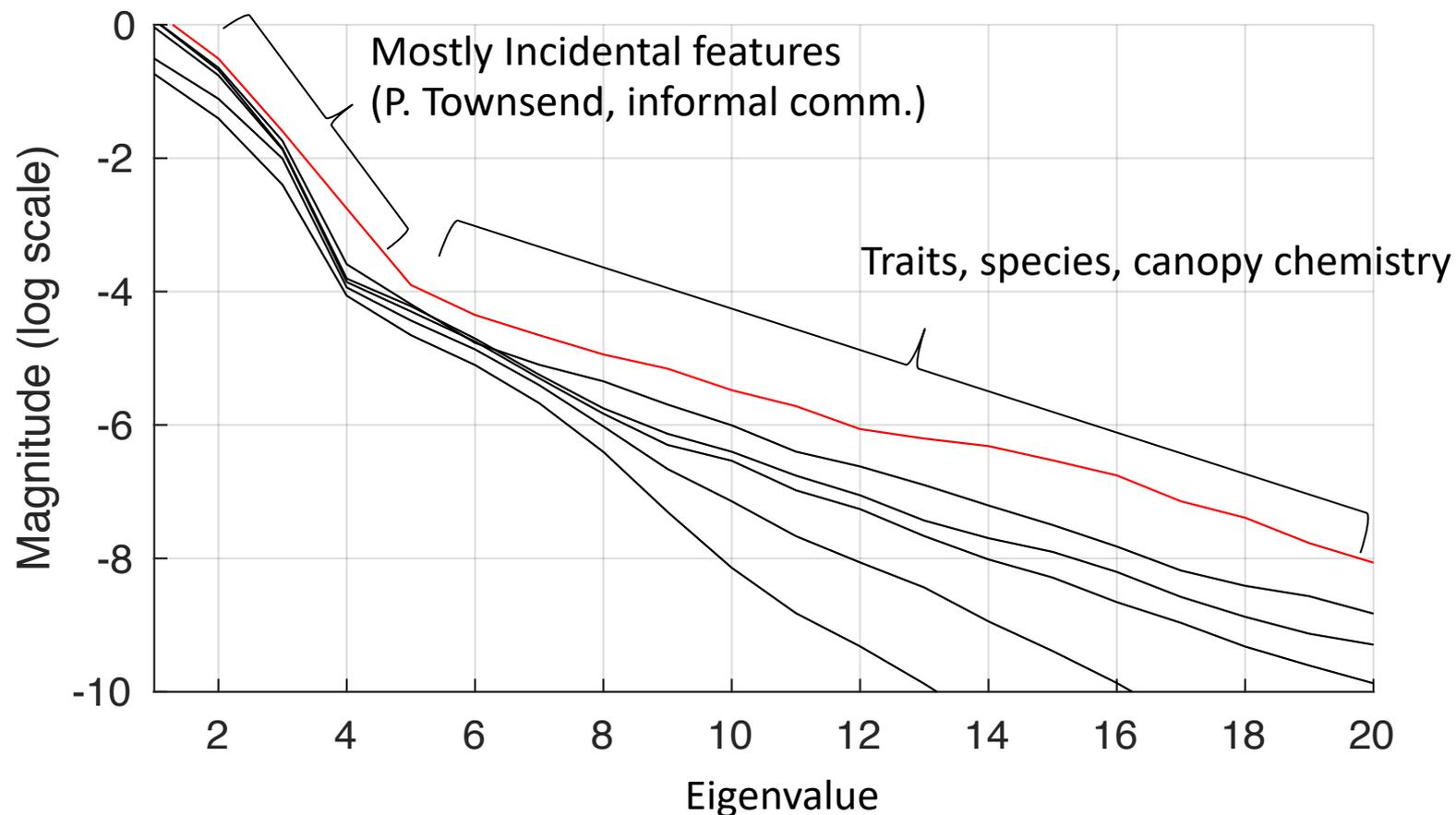


# Dimensionality of a vegetation library observed from orbit



Library from [Dennison, P. E., Gardner, M. E., 2000 <http://ecosis.org>].

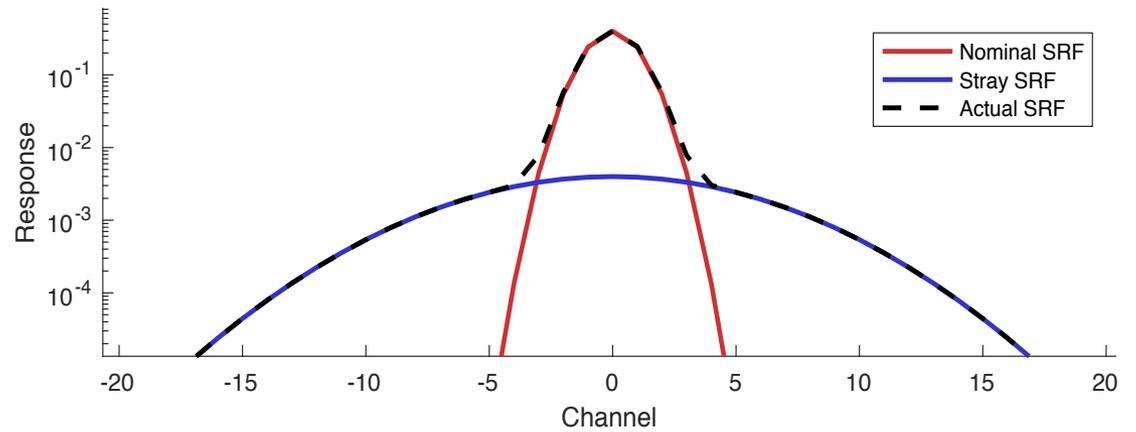
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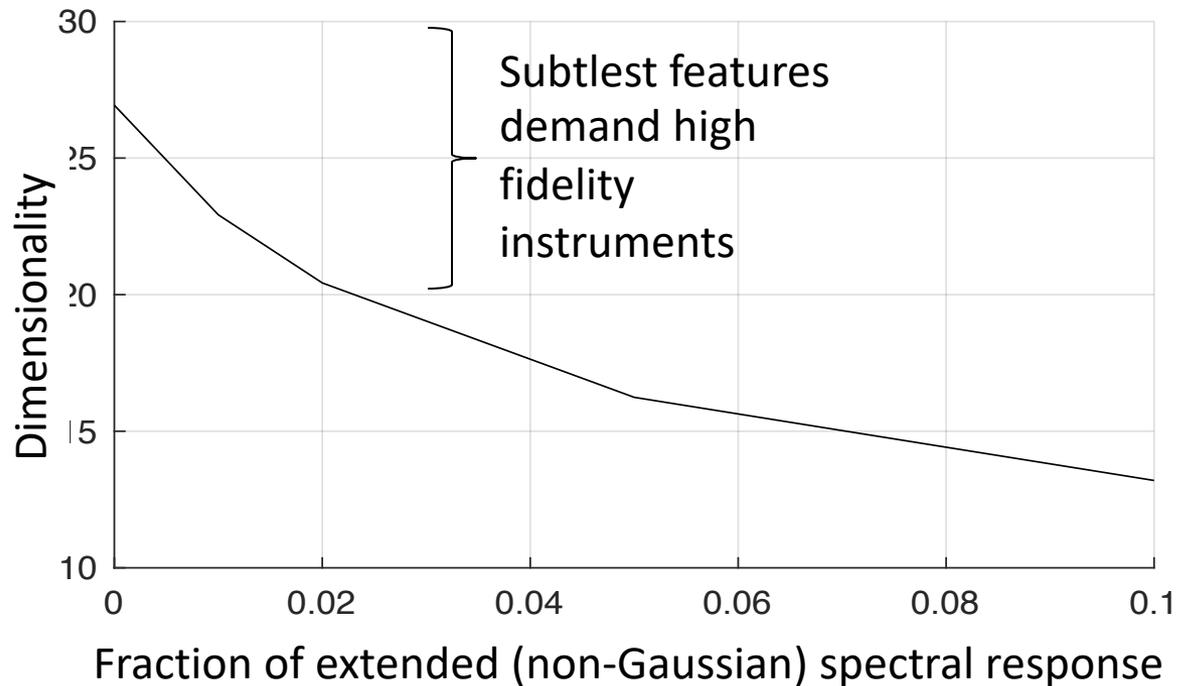
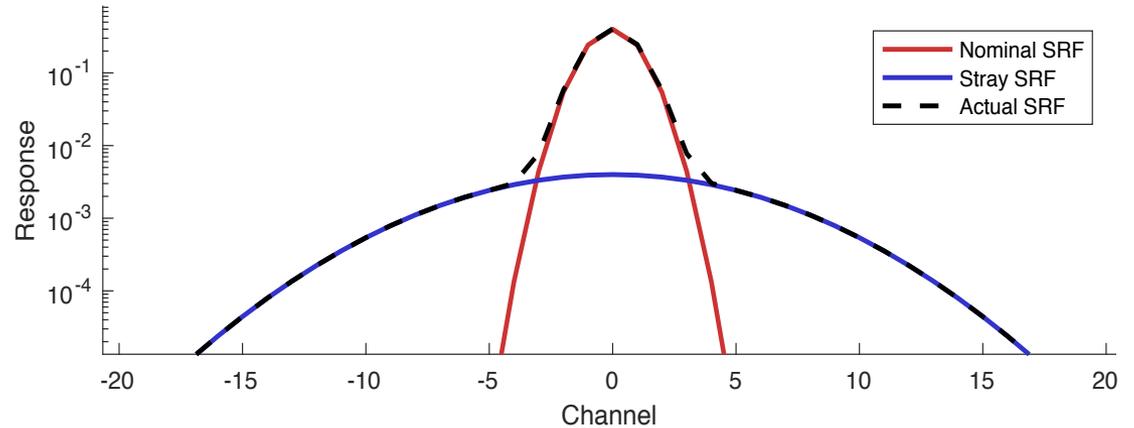
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# Stray spectral response



# Stray spectral response



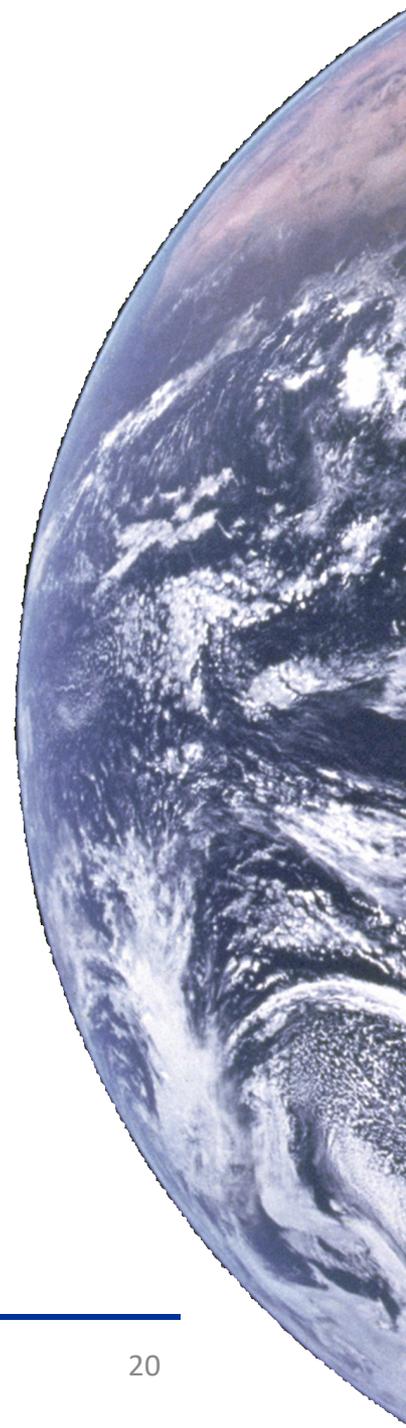
# Closing thoughts

Spectroscopy is the ideal instrument to measure Earth's diverse light field

Increasing instrument fidelity reveals ever-subtler surface properties

Algorithms must all improve in lockstep to unlock each new tier of surface phenomena

- Radiometric, spectral characterization
- Atmosphere and surface retrievals
- Ecosystem trait retrievals



# Thanks!

**NASA Earth Science Division:** HypsIRI preparatory campaign, AVIRIS-NG India Science Data Analysis program, Woody Turner and Jack Kaye.

**Colleagues** including Dave Schimel, Charles Miller, Joe Boardman, Sarah Lundeen, Ian McCubbin, and Charles Sarture.

## More information

Thompson, D. R., J. W. Boardman, M. L. Eastwood, R. O. Green (2017). “A large airborne survey of Earth’s visible-infrared spectral dimensionality,” *Optics Express*, 25:8, p. 9186-9195.

Rodgers, C. D. (2000) *Inverse Methods for Atmospheric Sounding: Theory and Practice*.

Thompson, D. R., Natraj, V., Green, R. O., Helmlinger, M. C., Gao, B. C., & Eastwood, M. L. (2018). “Optimal estimation for imaging spectrometer atmospheric correction,” *Remote Sensing of Environment*, 216, 355-373.

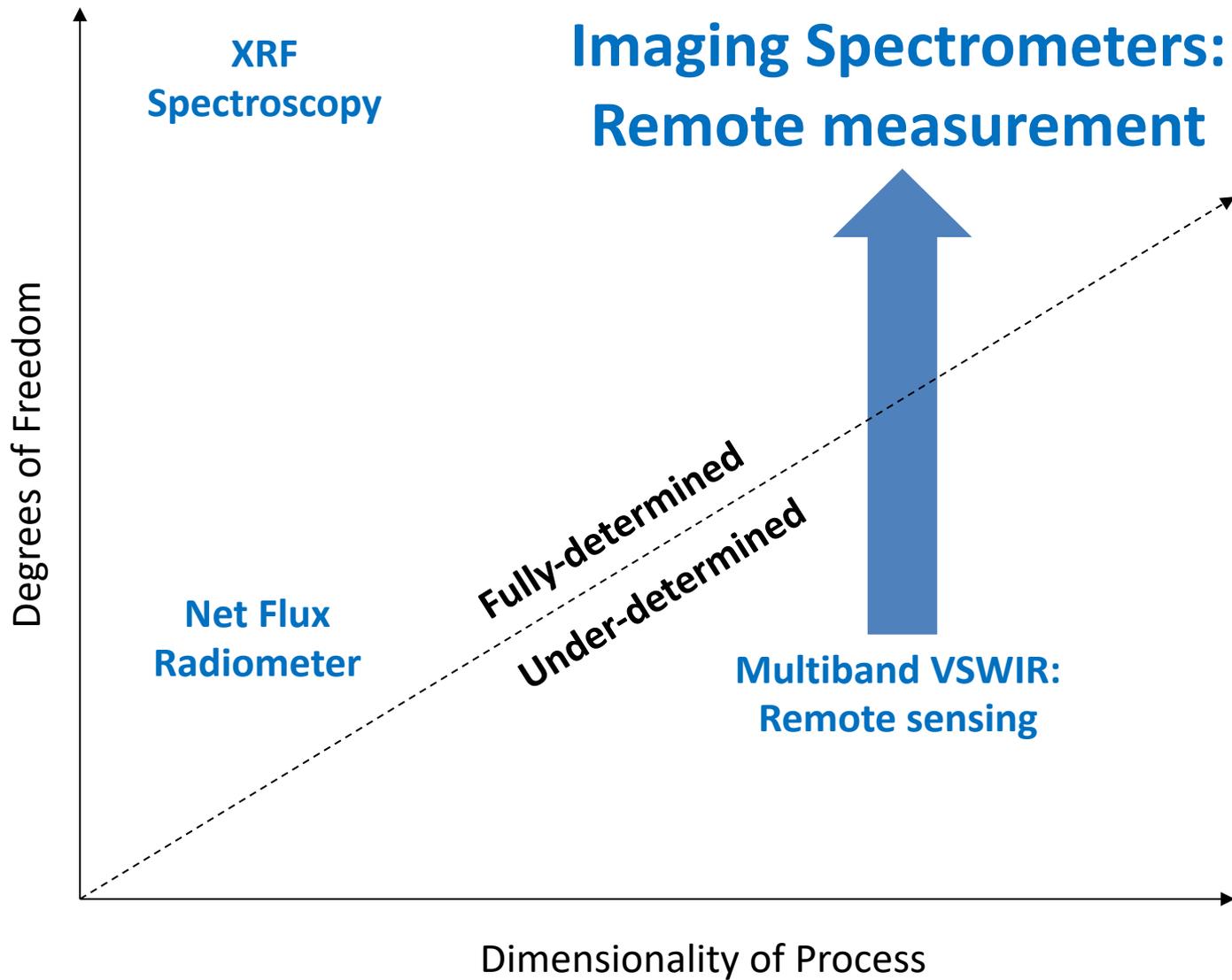
AVIRIS-C data is available from <http://aviris.jpl.nasa.gov>

AVIRIS-NG data is available from <http://avirisng.jpl.nasa.gov>

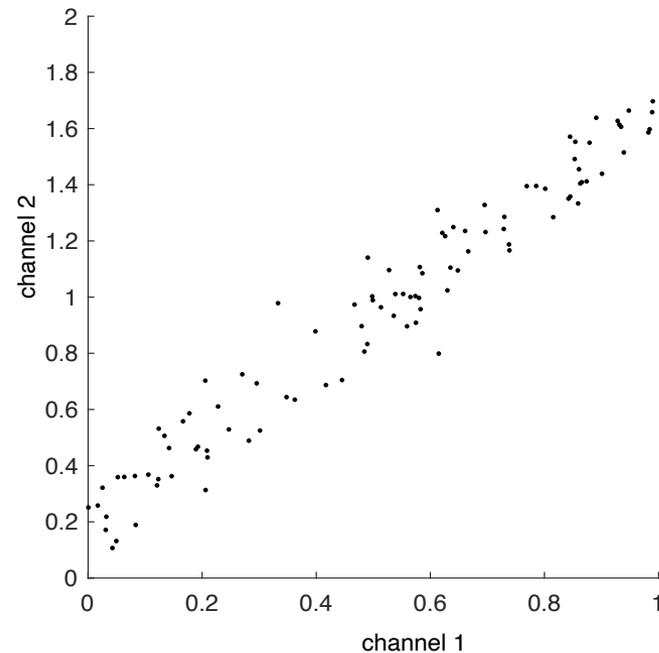
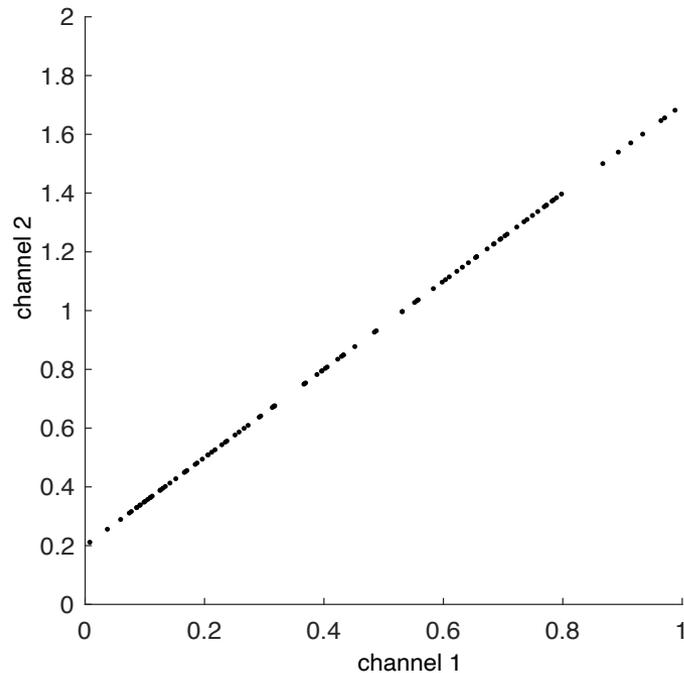
Code is available from <https://github.com/isofit/isofit>



**Backup**



# Dimensionality estimates must account for measurement noise



Laplacian Eigenmap code via Kye Taylor, Mathworks file exchange

# Some ways to estimate dimensionality [Wu et al., Proc. SPIE 2006]

- **Random Matrix Theory** [K. Cawse-Nicholson, IEEE T. Image Process. 2013]
- **Information Criteria** [H. Akaike, IEEE T. Automat. Contr, 1974]
- **Data Description Length** [J. Rissanen, Automatica, 1978]
- **Gerschgorin Radii** [Wu et al., IEEE T. Signal Proces, 1995]
- **Signal Subspace Estimation** [Bioucas-Dias and Nascimento, Proc. SPIE, 2005]
- **Neyman-Pearson detection theory** [Harsanyi et al., Proc. of Amer Soc. Photo. Rem. Sens, 1994]



# Jacobian matrix represents the observation

[Rodgers 2000; Thompson et al., 2018]

The Jacobian matrix represents the sensitivity of the observation system to a change in the true state. We form it using standard radiative transfer and instrument optical models.

$$K = \frac{\partial F}{\partial x}$$



# Gain matrix represents the inversion

[Rodgers 2000; Thompson et al., 2018]

The gain matrix incorporates unknowns that are not directly estimated, as well as the strength of the prior distribution and instrument/observation noise.

$$G = \frac{\partial \hat{x}}{\partial F} = (K^T S_n^{-1} K + S_a^{-1})^{-1} K^T S_n^{-1}$$

Observation noise covariance

Prior covariance



# Calculating the observed dimensionality

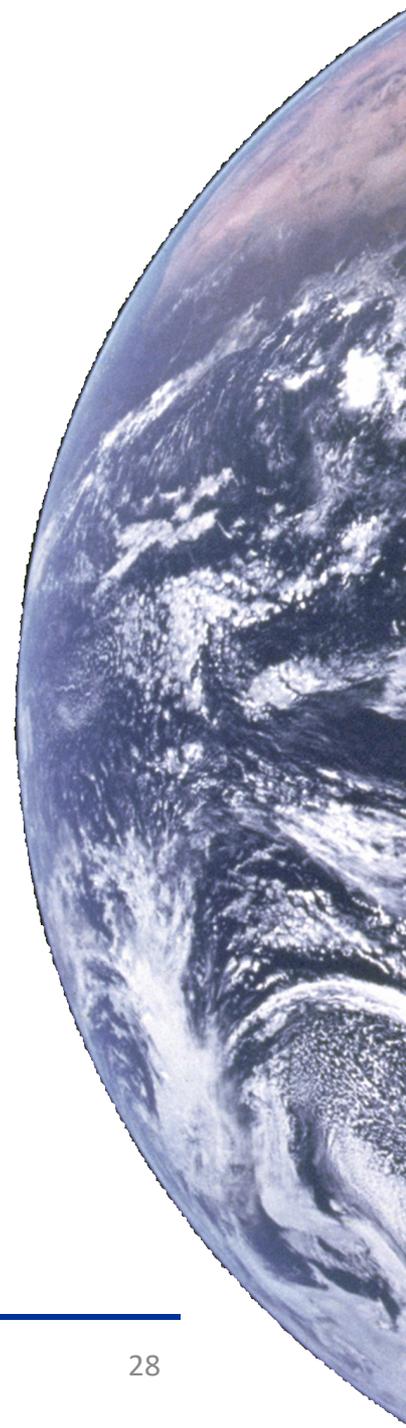
Singular Value Decomposition of the *target population covariance*:

$$UVD = \Sigma$$

Analyze the *estimated covariance*  $\hat{\Sigma}$  resulting from observation:

$$\hat{U}\hat{V}\hat{D} = \hat{\Sigma}$$

Here we use the linearized A matrix, but simulation-based alternatives can go farther...



# Variability due to measurement noise vs. unknown state parameters

Total observation noise

Jacobian WRT unknowns

$$\mathbf{S}_\epsilon = \mathbf{S}_y + \mathbf{K}_b \mathbf{S}_b \mathbf{K}_b^T$$

**Measurement noise  
(instrument effects)**

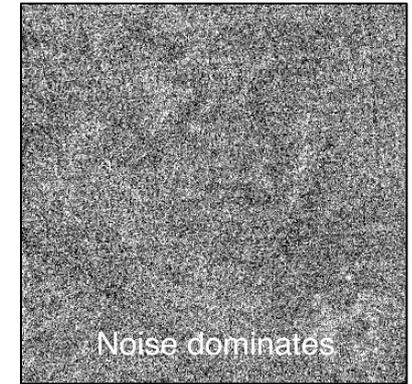
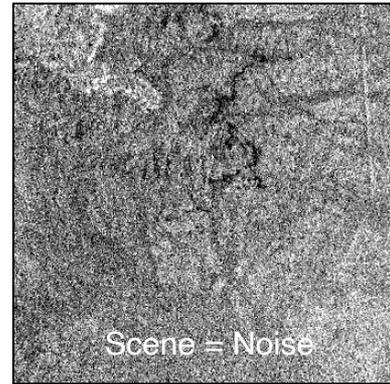
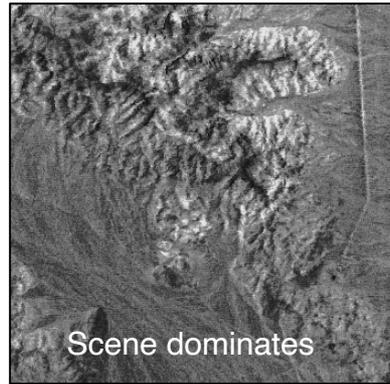
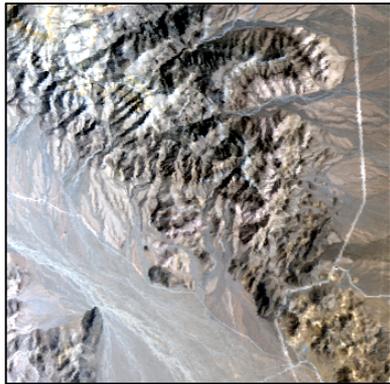
- Photon noise
- Read noise
- Dark current noise

**Unknown parameters in the  
observation system**

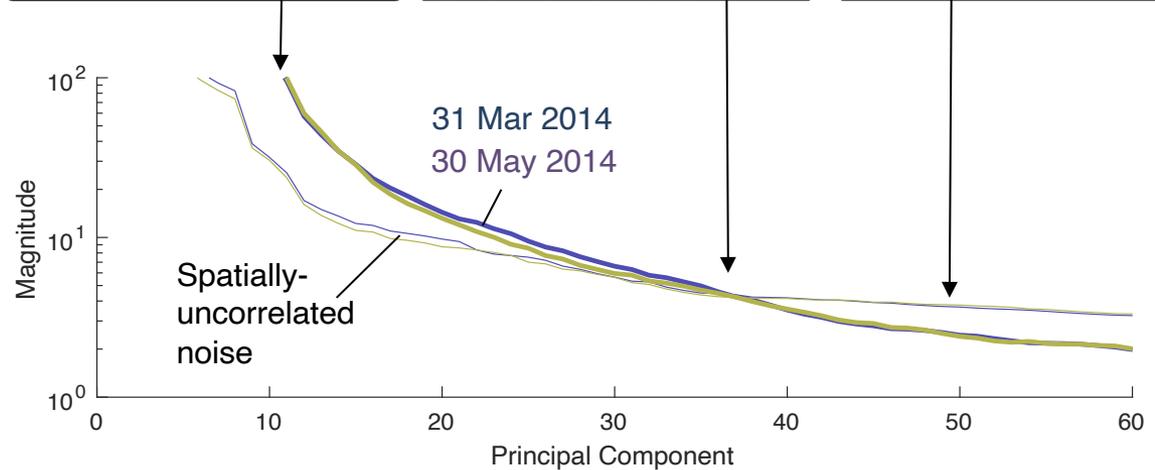
- Sky view factor
- H<sub>2</sub>O absorption coefficient intensity
- Systematic radiative transfer error
- Uncorrelated radiative transfer error

# Eigenvalue decay curves

[Thompson et al., *Optics Express* 2017]



R: 690nm  
G: 550nm  
B: 420nm



# Dimensionality of a vegetation library observed from orbit

